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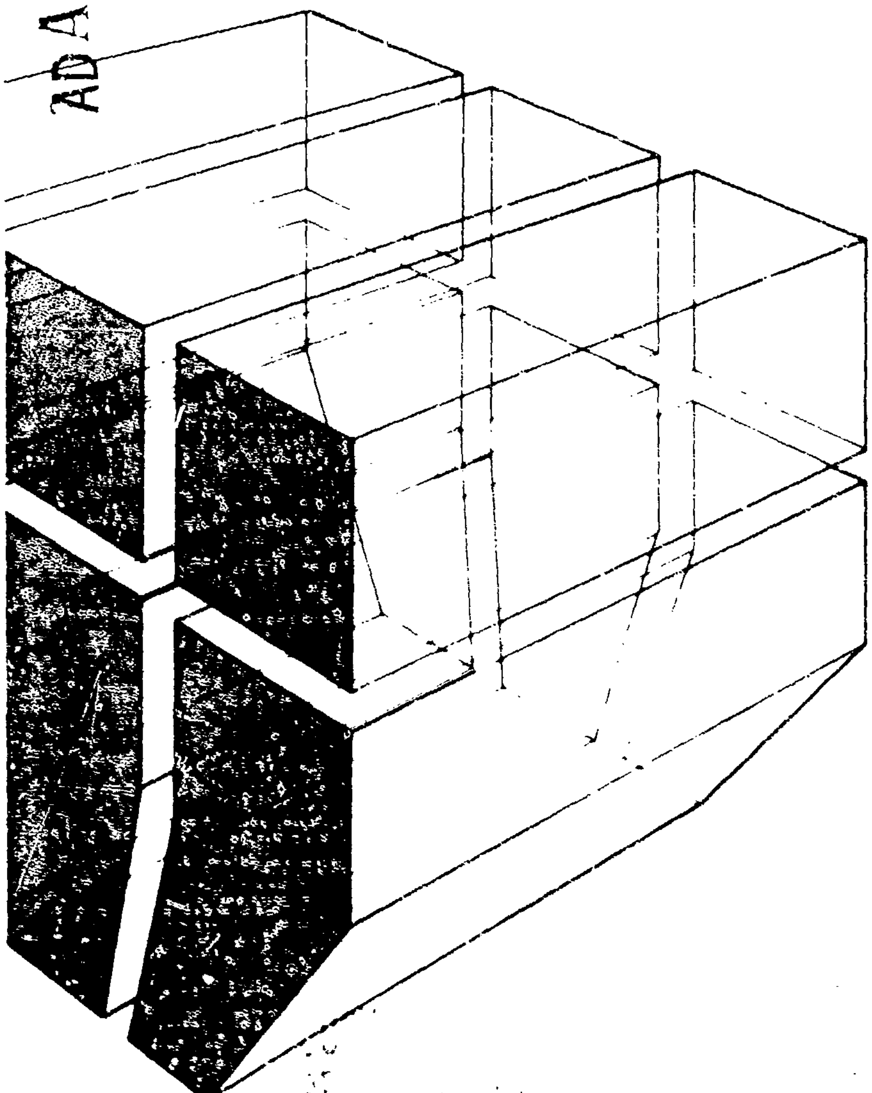
FUGITIVE DUST EMISSIONS FROM CONSTRUCTION HAUL ROADS



by
S. R. Struss
W. J. Mikucki

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In Fiscal Year 1972, a study was initiated (1) to examine the nature of environmental degradation resulting from construction, and (2) to formulate both a Contract Specification Writer's Guide containing environmentally protective specifications and a Resident Engineers' Guide with similar information to allow proper enforcement of the environmental specifications. These two guides were published as CERL Technical Reports E-72 (July 1975) and E-57 (May 1975), respectively. During the —

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development of these documents, two areas were noted to have a paucity of available information: (1) solid waste generation from construction and demolition activities, and (2) fugitive dust emissions from unimproved construction haul roads. To strengthen the guidance in the E-57 and E-72 reports, in-depth studies in the debris and dust areas were conducted. The results of the debris investigations are detailed in CERL Technical Reports N-14 (December 1976) for construction debris and N-15 (October 1976) for demolition debris.

This report provides details on a study which developed a model for predicting dust emissions from haul roads. The study examines the use of water as a palliative to control dust emissions. The study was conducted in two phases, and comparative data were obtained from a third, independently conducted phase.

The first phase was conducted under controlled conditions in an enclosed test track facility. Dust emissions caused by a loading frame mounted in the track were measured for a known soil under varying vehicle speeds and weights. In addition, soil water potential was monitored throughout each of the 18 tests. A model was developed from these results for predicting dust emissions when vehicle speed, vehicle weight, and soil water potential are known.

The second phase of the study, conducted in the field, used a 4 1/2-ton (4.1 metric ton) truck and a different soil type. Emissions were measured for various vehicle speeds, vehicle weights, and soil water potentials. Wind speed and direction were monitored continuously throughout each of the nine tests conducted. A model was developed to compare these data with the test track model.

In the third phase, the test track was filled with the soil used in the field and the procedure followed in phase one was repeated. Thus, data from the track and the field could be compared directly to check the accuracy of the track model. Comparing results from the two track phases indicated the influence of soil type on dust emissions.

The test track proved to be a useful tool for studying dust emissions, since it provided for close parameter control and eliminated uncertainty from atmospheric dispersion.

This study indicates that soil water potential, along with vehicle speed, vehicle weight, and soil type, are significant in the determination of dust emission rates. A relationship involving these parameters was developed which could prove useful in controlling dust emissions from construction sites.

FOREWORD

This study was conducted by the Environmental Engineering Team (ENE), Environmental Division (EN), of the U. S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Military Construction, Office of the Chief of Engineers (OCE), under Project 4A162121A896, "Environmental Quality for Construction and Operation of Military Facilities," Task T2, "Pollution Control Technology," Work Unit 006, "Application Tools for Protection of the Environment During Construction." Mr. R. Liebhardt was the OCE Technical Monitor. The QCR number is 1.03.006(2).

Assistants in this research were Jan Jerabek and Dan Kraybill. Appreciation is expressed to Dr. Ernest J. Barenberg, Professor of Civil Engineering at the University of Illinois, for making the Pavement Test Track available for use in this project, and to Dr. Barry Dempsey and Dr. J. J. Stukel, both of the Civil Engineering Department of the University of Illinois, for their technical assistance. Special appreciation is expressed to Mr. Thomas Irvin, technician at the Pavement Test Track, whose generous assistance was invaluable to the completion of this project.

Dr. R. K. Jain is Chief of EN, and Mr. W. J. Mikucki is Chief of ENE.

COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Dust emissions from construction haul roads can create many problems. The particulates generated are a health hazard to on-site workers, create a public nuisance, and when excessive, can create a safety hazard by reducing visibility.

Although commercial dust palliatives for treating road surfaces are available, they can be quite expensive.[1] Water, if readily available, can be an economical palliative, but only if applied at the proper rates. If watering rates are insufficient, control will be inadequate; if rates are excessive, materials and labor will be wasted.

State and Federal regulations limit the amount of particulates which can be emitted into the air. In the case of construction, the contracting agency is responsible for specifying compliance with these regulations. Emissions exceeding these allowable amounts would be a misuse of the environment. Currently, there are no definite guidelines for applying water as a dust palliative under various conditions. General guidelines exist but fail to consider all relevant factors and can result in excessive emissions or wasted resources. Monitoring emissions is the only certain way of meeting standards; however, the equipment and manpower requirements for this procedure make monitoring uneconomical. A simple, accurate system for determining the necessary watering rate under various conditions is needed so that standards can be met with a minimum amount of labor and materials.

Since previous studies[2] have found no correlation between soil moisture and dusting, no simple system has yet been developed.

Objective

This study had three objectives. The first was identification of possible factors which had led to previous conclusions that there is no correlation between soil moisture and dusting. The second goal

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[1] *Dust Control*, DA PAM 525-5 (Department of the Army, 1969), p 11.

[2] K. Axetell, C. Cowherd, Jr., C. M. Guenther, and G. A. Jutze, *Development of Emission Factors for Fugitive Dust Sources*, EPA 450/3-74-037, PB 238 262 (Midwest Research Institute, 1974); R. Dyck, *Fugitive Dust* (unpublished thesis, University of Illinois).

of the study was to determine whether there could be a moisture threshold for dusting below which one relationship would apply and above which another would apply. Such a situation would explain some of the inconsistencies encountered previously. The third goal was to develop an expression for the amount of dust emitted as a function of soil moisture, vehicle speed, vehicle weight, and soil type.

Scope

Dust emissions from unimproved roads were the primary focus of this study. Vehicle speeds ranged between 5 to 15 mph (8 to 24 kph) due to physical limitations of the test track apparatus. While these speeds are low with respect to the normal haul road speeds of 30 to 40 mph (48 to 64 kph), the model developed during this investigation provides an initial basis for estimation. The validity of this extrapolation can be quickly verified in the field, if more precise information is required. Due to variations in the number of wheels per vehicle, vehicle weight was expressed in units of pounds-per-tire for comparison. These loadings varied from a low of 1370 lb/tire (620 kg/tire) to a high of 2500 lb/tire (1130 kg/tire).

Since only two types of soil (Gooselake clay and Drummer silty clay loam) were used to determine the effect of soil type on dust emissions, a trend rather than a definite relationship was established involing this parameter.

Approach

To facilitate a detailed study of dusting, and to identify the reasons for inconsistencies in data reported by others, a scaled-down model of the process was designed in the first phase of the study to provide control of all variables. A relationship was developed from the data generated which describes dust emissions as a function of soil moisture, vehicle speed, vehicle weight, and soil type.

The second phase of the study involved a full-scale field model against which the track model could be checked under realistic conditions. By comparing these results, it was hoped that additional information could be gathered which either study alone would not provide.

While seeking an accurate means of monitoring soil moisture for this study, a relatively new parameter was encountered. This parameter, known as soil water potential, seemed to be a better measurement than percent moisture content, since it indicated how tightly the water was bound in the soil rather than just how much water was present. It was decided to monitor this parameter because of the information it supplied and the in-situ nature of its measurement.

In the third phase of the study, the test track used in the first phase was loaded with soil from the field site (second phase), allowing a direct comparison of track and field results to determine the track model's accuracy.

Technology Transfer

The predictive model developed herein should prove useful to Resident Engineer personnel for monitoring the environmental provisions of construction contracts. The model gives quantitative estimates of dust emissions from construction site haul roads under varying conditions of vehicle speed, vehicle weight, and soil water potential. Contractors required to meet such emissions limitations can use this procedure to determine optimum time and rate of water application.

2 EXPERIMENTATION

Phase 1

In the first phase of this study, a scaled-down model was designed using the University of Illinois Pavement Test Track[3] (Figure 1). It was felt that the degree of parameter control offered by this facility would make it useful for studying dust emissions. The track itself is an annulus with an inside diameter of 8 ft (2.4 m), an outside diameter of 25 ft (7.6 m), and a depth of 4 ft (1.2 m). For testing various materials placed in the track, it is equipped with a 16-ft (4.9-m)-long loading frame which rides on two 8.25 x 20-in. (20.96 x 51-cm) truck tires and which rotates around a vertical axis mounted in its center. The frame is electrically driven at speeds between 3 3/4 and 15 mph (6 and 24 kph) and can be loaded with steel bars to weights of 3700 to 6500 lb (1680 to 2950 kg). An oscillating mechanism attached to the frame causes it to cycle radially as it rotates. This causes the tires to cover a path 30 in. (76 cm) wide, rather than continuously loading the same narrow region. This facility is used primarily for testing the durability of pavements at an accelerated rate but was quite adaptable for studying dust emissions.

A 5-ft (1.5-m)-high enclosure consisting of a wooden frame covered with polyethylene sheeting was built to completely surround and cover the track (Figure 2). Fifty equally spaced 4-in. (10-cm)-diameter holes were cut in the enclosure's walls at a height of 1 to 2 ft (0.3 to 0.6 m) above the floor for air inlet. A 10-in. (25-cm) diameter hole was cut in the top center of the enclosure for ductwork leading to a cyclone collector. A door in one side of the enclosure allowed access to the track for watering and repairs.

The advantages of this arrangement over a field experiment were ability to adjust soil moisture easily, independence from variable weather conditions, and most important, elimination of atmospheric dispersion. In the field, wind speed, wind direction, and atmospheric stability must all be monitored and the Gaussian dispersion equation must be relied on. Each of these factors adds uncertainty to the final result. Previous studies[4] have determined that the standard Gaussian dispersion equation, although one of the best models available, is still only 50 percent reliable. The enclosed test track greatly reduces this uncertainty, since all air moving over the wheel path is directed past the collection unit. The capability of maintaining a consistent vehicle speed is also greatly improved by using an electrically driven frame rather than driving a truck on a rough road.

[3] H. L. Ahlberg and E. J. Barenberg, "The U of I Pavement Test Track - A Tool for Evaluating Highway Pavements," *Highway Research Record*, No. 13 (Highway Research Board, 1963), pp 1-21.

[4] *Meteorology and Atomic Energy 1968* (U. S. Atomic Energy Commission, 1968), pp 157-159.

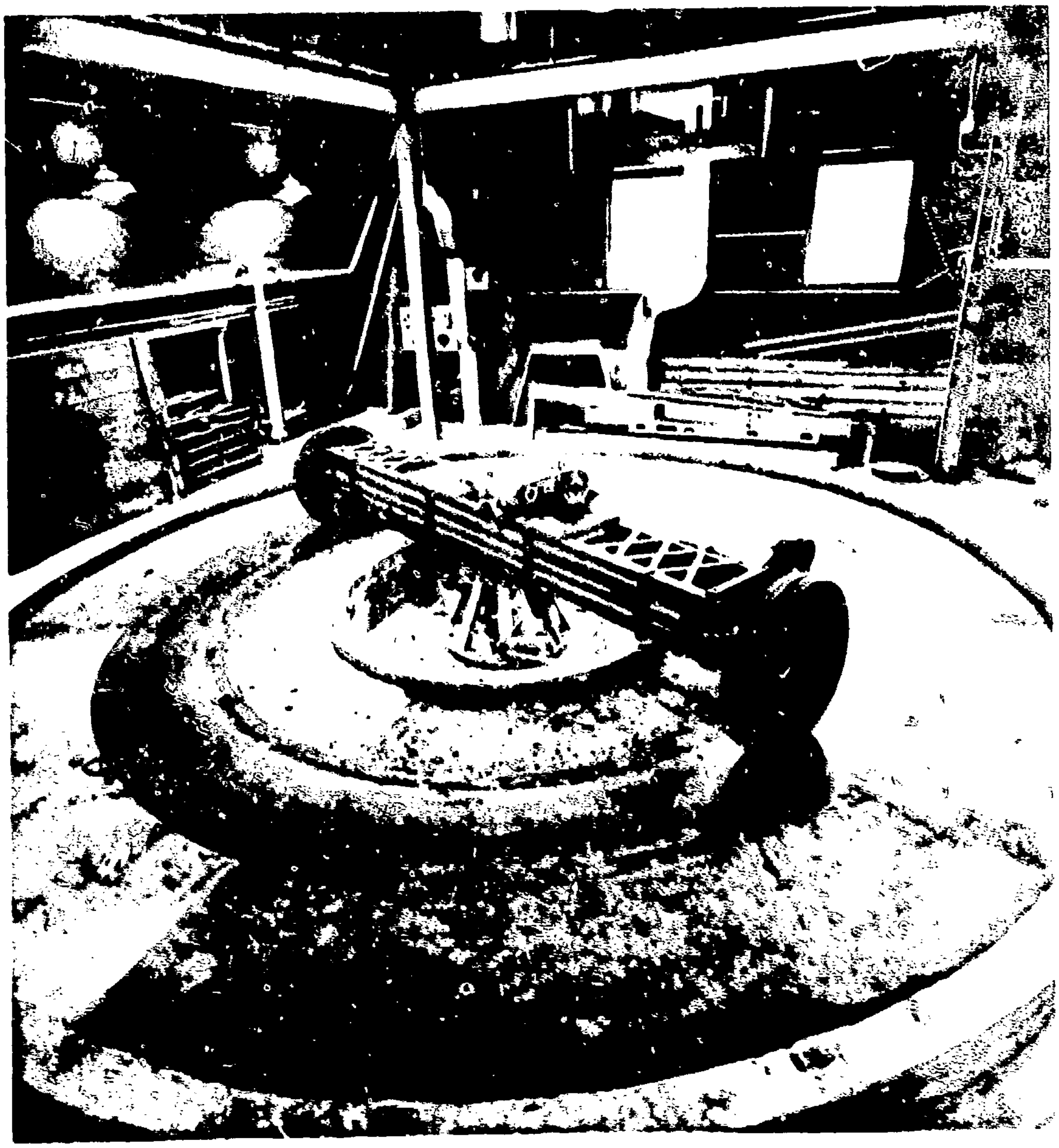
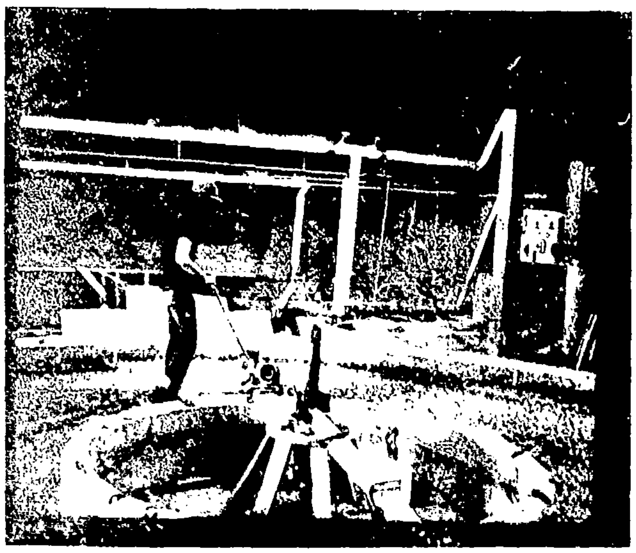
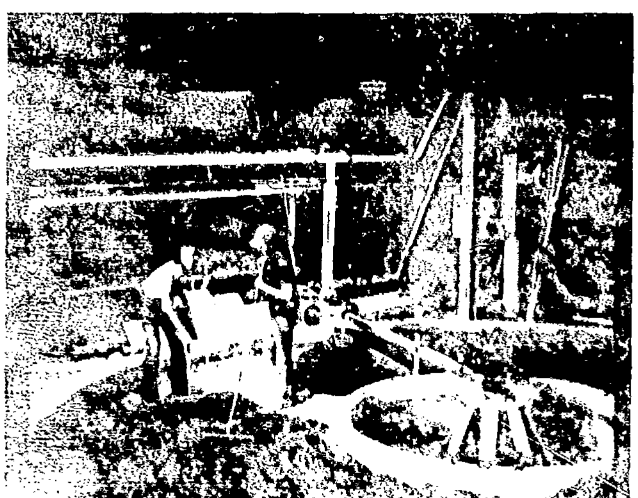


Figure 1. University of Illinois pavement test track.

a. Installing 3-ft (0.9-m) gravel sub-base.

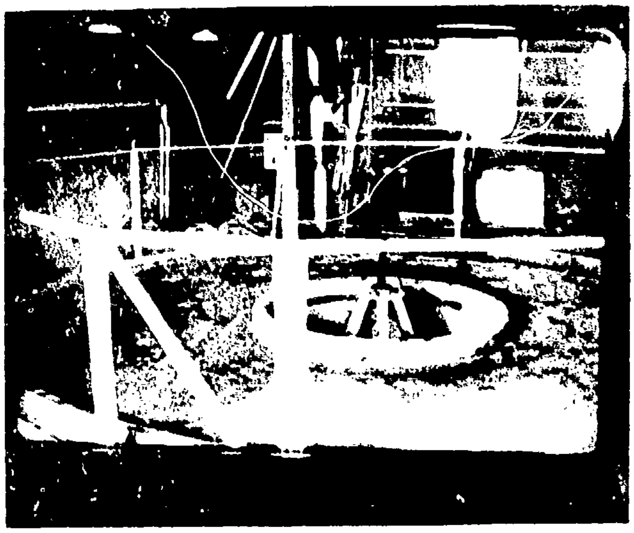


b. Compacting sub-base.

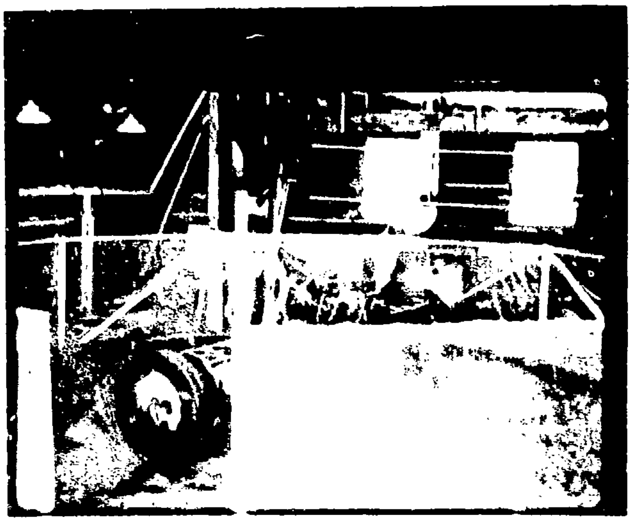


c. Installing 6-in. (15-cm) layer of Gooselake clay.

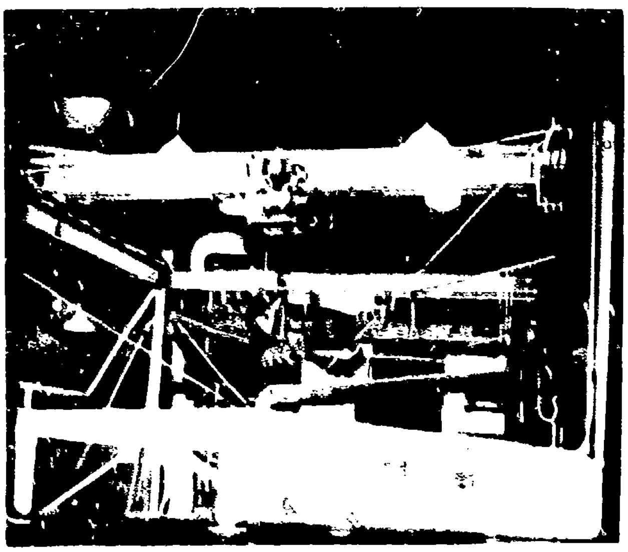
Figure 2. Test track construction sequence.



d. Compacted clay; wooden frame enclosure.



e. Loading frame and sheet plastic walls in place.



f. Completed structure; roof, ducting, and collection chamber in place.

Figure 2. (cont'd).

For this study, the track was filled with 3 ft (0.9 m) of crushed stone subgrade and 6 in. (15 cm) of compacted Gooselake clay (plastic limit = 16, liquid limit = 30, silt content = 87 percent). The loading frame was used at its three higher speeds of 5, 7 1/2, and 15 mph (8, 12, and 24 kph) and at weights of 3700, 4500, and 4900 lb (1680, 2040, and 2220 kg) to simulate typical haul road conditions. It should be noted that since the frame has only two wheels, it is modeling one-third of a six-wheeled vehicle and must be weighted to one-third the weight of such a vehicle. These three weights would therefore represent actual truck weights of 11,100, 13,500 and 14,700 lb (5040, 6120, and 6660 kg), respectively.

A sampling apparatus was built along the duct connecting the enclosure to the cyclone that consisted of a plexiglass box fitted with two high-volume air sampler (hi-vol) heads. The heads were joined to their respective vacuum motors via 4-in. (10-cm) diameter flexible ducting and were removable from the plexiglass box to allow replacement of filter papers. When in operation, the hi-vols would pull a portion of the dust-laden air from the 10-in. (25 cm) duct and collect the particulates on weighed filter papers. A mass flow analysis (see Appendix A) was performed to determine the ratio of collected mass to total mass of dust traveling through the 10-in. (25-cm) duct. Four soil psychrometers (see Appendix B) used to measure soil water potential were buried in the wheel paths of the track at a depth of 0.5 in. (1.3 cm) and were connected to a single readout unit outside the enclosure. A Coefficient of Haze (COH) monitor with a strip chart recorder kept an additive total of the visibility within the enclosure during each run. These data were taken to help determine a possible moisture threshold for dusting.

Throughout each test, dust emissions and soil water potential were monitored, while vehicle speed and weight were held constant. The study was therefore in the form of a two-way factorial experiment. Ideally, many different combinations of speed with weight should have been run to insure a high degree of reliability; however, due to time constraints, it was necessary to conduct the minimum number of tests which would produce a reliable relationship. Two speeds and two weights would have been sufficient if the relationship were linear, but this was not known to be the case; therefore, at least three values of each parameter were required to develop a reliable relationship.

Using three vehicle speeds and three vehicle weights, it was necessary to conduct nine tests to exhaust all possible combinations. Two sets--a total of 18 tests--were run to improve the reliability of the results. The speeds and weights were chosen randomly by the rolling of a die before each test. Figure 3 is a diagram of the scheme into which the 18 tests fit. Note that the results of test 3 were discarded and an additional test run in its place.

	Speed 1	Speed 2	Speed 3
Weight 1	Test 8; Test 16	Test 7; Test 15	Test 2; Test 19
Weight 2	Test 17; Test 10	Test 4; Test 14	Test 9; Test 11
Weight 3	Test 1; Test 13	Test 6; Test 12	Test 5; Test 18

Figure 3. Testing matrix.

Before conducting a test, the track was wet down with a garden spray and allowed to stabilize overnight. The next morning the weight and speed for the test were randomly chosen and adjusted. Clean filter papers and flow rate recorder charts were placed in the hi-vols. The test was started by turning on the loading frame, hi-vols, cyclone, and COH monitor and by taking the first soil water potential readings. During the test, hi-vol filter papers were changed and soil psychrometer readings were taken at intervals of 0.5 to 2 hours, depending on the dust emission rate. An average high-speed test would require approximately 3 hours to produce visibly excessive emissions, whereas an average slow speed test lasted approximately 8 hours. For comparison, an attempt was made to run all tests over the same range of soil psychrometer readings.

After the test track was modified, a shakedown period was required to eliminate some early problems. The steel bars originally used to weight the frame required too much time to remove and replace, making random weight selection difficult. At first, sandbags were tied to the top of the frame, but jarring and centripetal force caused them to tear. Next, plywood boxes were bolted to the frame to hold the sandbags, but these also failed. The boxes were then reinforced with angle iron and screws, but the screws were pulled from the wood by the force of the sandbags. Finally, time was sacrificed and the steel bars were used.

Originally, 4-in. (10-cm)-diameter flexible plastic ducting was used to connect the hi-vol heads to their vacuum motors. The vacuum pulled by the hi-vols quickly collapsed the ducts. This problem was solved by switching to flexible metal ducting.

Electrical interference was a problem with the soil psychrometers. Using them indoors required a different arrangement, since they were originally designed for use outdoors away from electrical equipment. Since the psychrometers' output was in the microvolt region and long leads had been used to connect them to the readout unit, very small alterations in the surrounding electric field would affect the readings. This situation was remedied by shielding the wires leading to the readout unit and grounding both the shielding and the readout casing.

After the shakedown was completed and the procedure for conducting a test was refined, the test track proved to be a useful tool for studying dust emissions, providing parameter control and repeatability not possible in the field.

The disadvantage of using a test track is one inherent in any model: it does not represent exactly the phenomenon it is simulating. The main inaccuracy in this model resulted from the turning action of the tires. Due to the restraint of the center post, there was no centripetal force like that created by a truck turning a corner; however, there was some rubbing action of the tires due to their being directed tangent to rather than parallel to their path. It appeared from observations that this rubbing had little influence on the behavior of the road and that any influence it did have on results was accounted for by comparing track data to field data.

Another discrepancy in the model was that the loading frame had two wheels, whereas a vehicle in the field would have at least four. Therefore, the dust was measured in units of grains per tire-mile rather than in units of grains per vehicle-mile in both the track and later in the field. It was assumed that a two-wheeled vehicle would produce one-third as much dust as a six-wheeled vehicle having the same weight per tire loading.

Phase 2

The second phase of the study was conducted in the field to observe dusting under realistic conditions and to test the accuracy of the test track model. A dirt road was constructed by plowing and roto-tilling a section of land just north of the Construction Engineering Research Laboratory, Champaign, IL. The advantages of this arrangement over an off-property site were saving time in transporting equipment, having sole use of the roads with no public interference, and being able to leave equipment in the field without having it disturbed. Three roads 10 ft (3.1 m) wide by 300 ft (90 m) long were constructed. They intersected in the middle and were oriented north-south, northeast-southeast, and northwest-southeast, so that, theoretically, a test could be conducted regardless of wind direction. Due to highly variable winds, however, there were times when none of the roads were usable. A 4 1/2-ton (4.1-metric ton) flat-bed truck with two axles and six wheels generated the dust, and steel columns weighing 850 lb (390 kg) apiece were used to adjust vehicle weight. An engine-generator mounted on a support vehicle powered three high-volume air samplers and a recording wind-vane anemometer. The same soil psychrometers were used as in the test track, but a battery power pack was used instead of line current.

Each test was run for 1 hour. Before each test, the anemometer was set up to determine which road was most perpendicular to the average wind. The support truck was then moved downwind of this road and the three hi-vols arranged, two at a distance of 50 ft (15.2 m) from the road and one at a distance of 100 ft (30.5 m) (see Figure 4). Three soil psychrometers had previously been buried in each of the three roads, so all that was necessary was connecting them to the readout unit with clip leads. The weight of the truck had already been adjusted with the steel columns and measured with portable truck scales. The vehicle speed was randomly chosen before each test.

To conduct a test, the filter papers were weighed and placed in the hi-vols, and the anemometer recording charts and the hi-vols were started as the truck made its first pass. During the test, psychrometer readings were taken every 15 min, and average hi-vol flow rates were noted. Since the truck was being considered as many vehicles passing a given spot rather than one vehicle traveling a given distance, the number of passes, not the miles traveled, was recorded. At the end of the test, the hi-vol papers were reweighed and the increases in their weights were recorded. Three vehicle speeds and three vehicle weights were used, for a total of nine tests.

Two of the problems encountered in the field phase were variable winds and occasional malfunctioning of the engine-generator. In addition, weeds overtook the roads during a period of wet days, making it necessary to rework them. The steel columns used to weigh the truck had a tendency to slide, making it necessary to secure them to the bed. The necessity for releasing and restoring the restraints greatly extended the time required for changing vehicle weight. If truck weight had been randomized, much more time would have been spent changing weights than running the tests. However, since the three different roads were used randomly, depending on the wind direction, it was felt that weight could be increased throughout the set of tests without significantly affecting the results.

It was first thought that organic matter left in the soil would alter conditions, making more of a mat than a dirt road, thereby changing dusting characteristics; however, when the plants decomposed, any remnants binding the soil were unnoticeable. Also, in an actual haul road situation, the roads are often constructed on grassy fields and therefore would resemble the test roads very closely. Even the turnarounds at the ends of the test roads emitted dust after a few tests, although they had not been plowed.

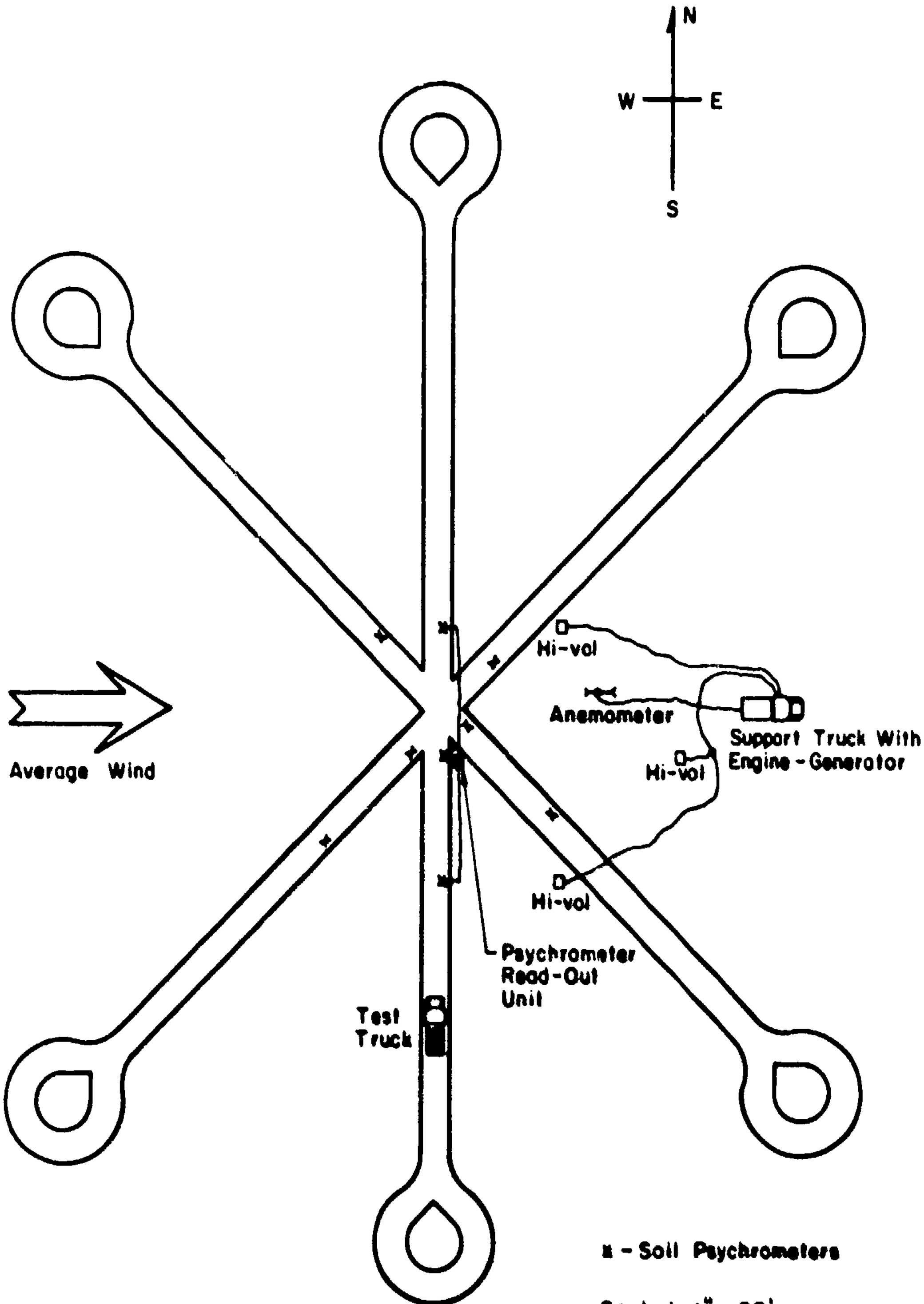


Figure 4. Field site.

Figure 4. (cont'd).

Maintaining a steady truck speed throughout the test was also a minor problem. Since the roads were rough, the speedometer usually oscillated over a range of at least 5 mph (8 kph). With practice, however, the average reading could be adjusted and held. It can be seen from the data in Appendix C that speed was reasonably well controlled from the number of passes made at any given speed.

During the field tests, it was noticed that some of the dust generated became trapped in ground vegetation before reaching the hi-vols. The dispersion equation used to calculate the dust emission rate from concentrations measured by the hi-vols assumes complete reflection at the surface, and therefore would indicate lesser dust emissions than had actually occurred. It was impossible to measure the amount of dust actually trapped in this manner, but the amount was not considered to be significant.

Phase 3

Finishing the test track and field tests completed the experimental phase of this work unit. However, one of the project assistants continued the study as partial fulfillment of requirements for an advanced degree and has made his data available for inclusion in this report.

This phase of the study used the same test track employed in the first phase, but now loaded with soil from the field test site. Nine tests were run with the same vehicle weights and speeds and with the same procedure used in the first phase. Since soil types were identical, track and field results could be compared directly, indicating the test track model's accuracy. Also, by comparing the results of the two track studies, the general influence of soil type on dust emissions could be indicated.

3 DATA REDUCTION

Track Data

The data in Table 1 were collected during the first phase of the study, which involved using the Gooselake clay in the test track. These data represent one complete test at a speed of 7.5 mph (12 kph) and a loading of 2450 lb/tire (1110 kg/tire).

The soil psychrometer readings are converted from microvolts to atmospheres of tension (the conventional units for expressing soil water potential) by using the conversion factor given in the psychrometer instruction manual[5] (0.47 microvolts/atmosphere of tension).

From the change in weights of the hi-vol papers, the hi-vol flow rates, the time duration, and the ratio of indicated dust concentration to actual dust concentration, the dust concentration in the duct leading from the enclosure can be determined as follows:

$$\frac{\Delta W_1 + \Delta W_2}{CFM_1 + CFM_2} \cdot \frac{1.54 \times 10^{-2}}{0.90 \cdot t \cdot 60} = C \qquad \text{[Eq 1]}$$

where:

ΔW_1	=	Change in weight of first hi-vol paper in milligrams
ΔW_2	=	Change in weight of second hi-vol paper in milligrams
CFM_1	=	Average flow rate through first hi-vol in cubic feet per minute
CFM_2	=	Average flow rate through second hi-vol in cubic feet per minute
t	=	Time in hours
1.54×10^{-2}	=	Conversion factor in grains per milligram
0.90	=	Percentage of total dust concentration indicated by hi-vols as determined by probe analysis
60	=	Conversion factor in minutes per hour
C	=	Dust concentration in the duct in grains per cubic foot.

[5] *Instructions for the MJ55 Psychrometer Microvoltmeter* (unpublished manual) (Wescor, Inc.).

Table 1

Raw Data for Test 6 in First Phase

Time (hr)	Psy 1 (μV)	Psy 2 (μV)	Psy 3 (μV)	Psy 4 (μV)	Psy Avg. (μV)	ΔW sum (grains)	ΔW sum (grams)	Q sum (cu ft/min)	Q sum (m^3/min)
0.00	15.5	5.6	9.9	6.5	9.4				
0.50	17.1	7.1	12.8	9.6	11.7				
1.00	16.9	6.6	14.1	10.5	12.0	1.2639	0.0819	74.5	2.00
1.50	18.6	7.2	16.6	12.3	13.7				
2.00	17.5	7.7	17.1	12.1	13.6	1.8796	0.1218	74.0	2.10
2.50	17.8	7.5	17.6	14.1	14.3				
2.95	18.6	7.7	17.5	15.1	14.7	4.6157	0.2991	75.0	2.12
3.40	19.8	8.5	18.8	16.4	15.9				
3.75	20.0	7.0	19.5	17.5	16.0	7.4907	0.4854	73.5	2.08
4.50	21.7	9.6	21.3	19.7	18.1				
4.75	22.4	10.5	21.0	18.5	18.1	14.954	0.9690	73.0	2.07
5.15	22.6	12.1	22.2	20.6	19.4	9.8163	0.6361	74.0	2.10

By using the speed of the loading frame, the dust concentration just calculated, and the air flow rate through the duct, the dust emission rate can be determined. Since the time duration for both measurements was identical, it cancels out of this calculation.

$$C \cdot 3590 \cdot 60 / S = D \qquad \text{[Eq 2]}$$

where:

C = Dust concentration in the duct in grains per cubic foot

3590 = Flow rate through the duct in cubic feet per minute

60 = Conversion factor in minutes per hour

S = Speed of loading frame in miles per hour

D = Dust emission rate in grains per vehicle mile.

As mentioned before, since the loading frame had two tires and the truck used in the field had six, units of weight in pounds per tire and dust emission rates in grains per tire-mile were used to allow direct comparison of the two test results. The previously calculated dust emission rate must therefore be divided by two, since two tires had generated the calculated dust.

Table 2 shows the final form which the data takes after these transformations and Figure 5 is a plot of these data on linear scales.

A linear regression analysis was performed on the data from all 18 tests using an SPSS Multiple Regression program. The parameters were defined as: D (dust emission rate), T (soil water potential), W (weight per tire loading), S (speed), and R (a test parameter). R was assigned the value of zero for the first nine tests and a value of one for the second set of nine tests. If R then proved to be statistically significant in the determination of D, it would indicate a change in dusting characteristics with time, possibly making it necessary to account for the age of a road when controlling dust emissions.

The following combinations of variables were used in the analysis:

$$D = f(T, W, S, R) \qquad \ln D = f(T, S, \ln \sqrt{W})$$

$$\ln D = F(T, W, S, R) \qquad D = f(T^{0.3}, S^{0.3}, W)$$

$$\ln D = f(\ln T, W, S, R) \qquad \ln D = f(T, W, S)$$

$$\sqrt{D} = f(T, W, S, R) \qquad D = f(e^{T}, e^{S}, W)$$

Table 2

Reduced Data for Test 6 in First Phase

Time (hr)	Psychrometer Average (atmospheres of tension)	Dust Output (grains/tire-mi)	(gm/tire-km)
0.00	20.0		
0.50	24.9		
1.00	25.5	4.51×10^{0}	1.82×10^{-1}
1.50	29.1		
2.00	28.9	6.75×10^{0}	2.72×10^{-1}
2.50	30.4		
2.95	31.3	1.72×10^{1}	6.93×10^{-1}
3.40	33.8		
3.75	34.0	3.39×10^{1}	1.36×10^{0}
4.50	38.5		
4.75	38.5	5.45×10^{1}	2.19×10^{0}
5.15	41.3	8.82×10^{1}	3.55×10^{0}

$D^{0.4} = f(T,W,S,R)$ $\qquad$ $D = f(e^{T+S}, w)$

$D^{0.3} = f(T,W,S,R)$ $\qquad$ $D = F(T \cdot W \cdot S)$

$\ln D = f(TS, \ln W)$ $\qquad$ $D = f(T^{3.3}, S^{3.3}, W)$

$$D = f(T^{3.3}, S^{3.3}, \sqrt{W})$$

$\ln D = f(T,S,W,TS,TW,SW,TSW,T^2,S^2,W^2)$ $\qquad$ $\ln D = f(T,S,W,TS,TW,SW,TSW)$

$\ln D = f(T,S,W,T^2,S^2,W^2)$ $\qquad$ $\ln D = f(T,S,W,S^2)$

$\ln D = f(T,S,S^2)$ $\qquad$ $\ln D = f(T^2,S^2,W^2)$

$\ln D = f(T,W,S^2)$ $\qquad$ $\ln D = f(T,S^2)$

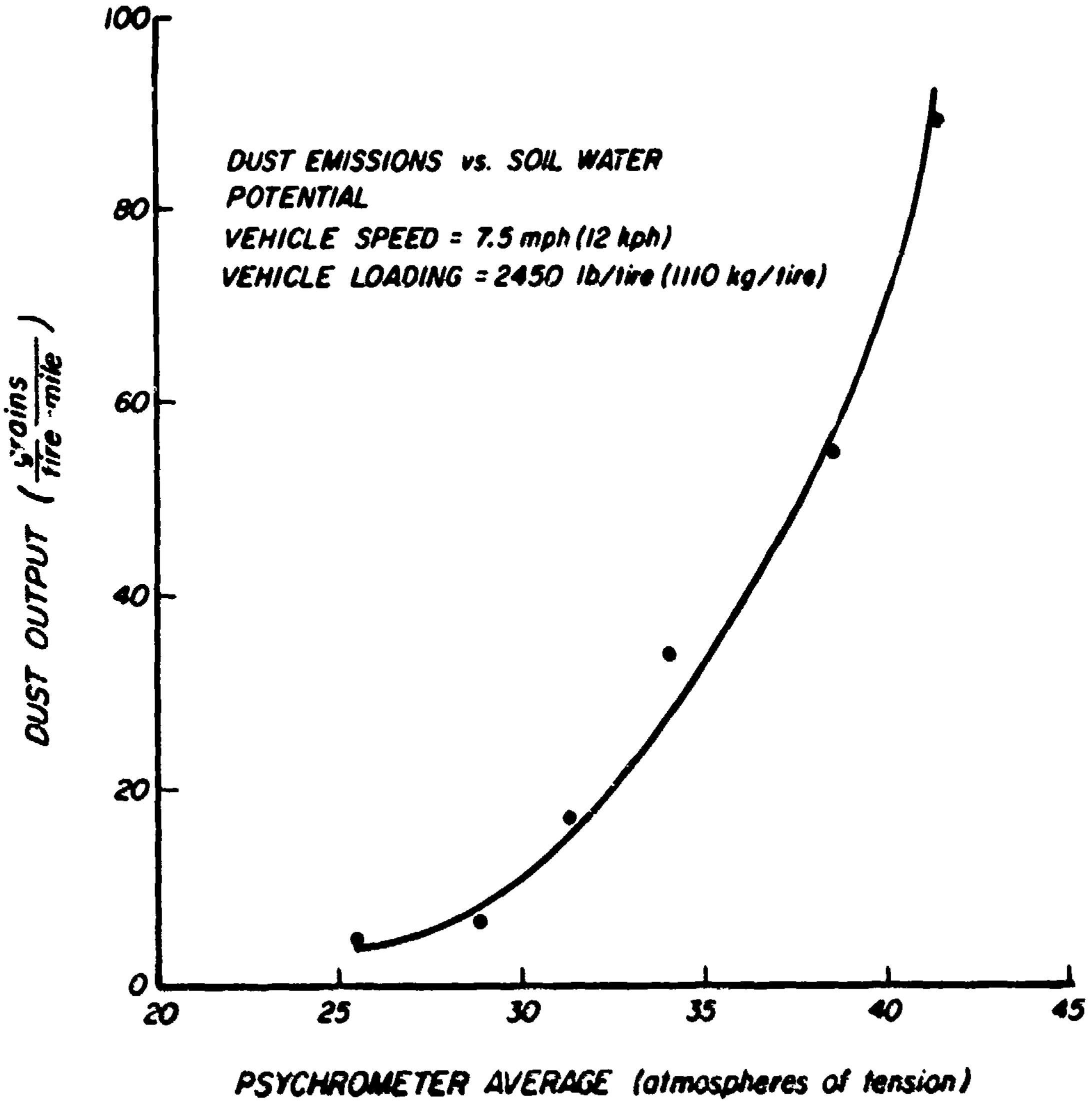


Figure 5. Dust output vs. soil water potential for test 6--first phase.

The test used to determine the statistical significance of each variable involved the following forms:

$$\ln D = f\ (T,W,S,R)$$

$$\ln D = f\ (W,S,R)$$

$$\ln D = f\ (T,S,R)$$

$$\ln D = f\ (T,W,R)$$

$$\ln D = f\ (T,W,S)$$

The results of this run indicated that T, S, and W were all significant at the 95 percent confidence level, but that R was not. The model which had the greatest correlation with the data was rerun with R omitted, resulting in the following equation:

$$\ln D = -5.37 + 0.12T + 0.21S + 0.90W \qquad \text{[Eq 3]}$$

The correlation coefficient for this relationship with the data from all 18 tests was r = 80, and the standard error was 0.94 over a range of -0.55 to 5.34.

Field Data

The data collected in one field test are listed in Table 3. In this test, vehicle speed was 7 mph (11 kph) and vehicle loading was 2500 lb/tire (1130 kg/tire). The wind speed, wind direction, and vertical dispersion coefficient (σ_Z) were calculated using time-averaged readings taken from the charts produced by the recording wind-vane anemometer. Time intervals of 225 sec were used to reduce the speed data, and 40-sec intervals were used to reduce the azimuth data. The close time intervals on the azimuth data were required because these data were also used to determine σ_Z. According to Pasquil,[6] this method is reliable only when small time intervals are used. The method involves finding the standard deviation in the azimuth data and using this value to pick a stability class according to the scheme shown in Table 4.

Knowing the stability class and the downwind distance from the source, σ_Z can be determined from the graph found on page 9 of the *Workbook of Atmospheric Dispersion Estimates.*[7] The downwind distances used in this study were less than 100 m, so it was necessary to extrapolate down to 10 m on this graph. It was assumed that this is a valid process.

Using the average wind speed and direction, the stability coefficient, the estimated plume centerline height, and the measured concentration of dust given by the hi-vols, the dust emission rate was calculated for each test, using the line source equation found in the *Workbook of Atmospheric Dispersion Estimates.*[8]

$$X\ (x,y,o,H) = \frac{2q}{\sqrt{2\pi} \cdot u \cdot \sigma_z \cdot \sin\phi} \exp\left[-1/2 \left(\frac{H}{\sigma_z}\right)^2\right] \qquad \text{[Eq 4]}$$

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[6] *Meteorology and Atomic Energy 1968* (U.S. Atomic Energy Commission, 1968), pp 101-103.

[7] *Workbook of Atmospheric Dispersion Estimates*, No. AP-26, PB 191-482 (U.S. Environmental Protection Agency, 1974), p 9.

[8] *Workbook of Atmospheric Dispersion Estimates*, p 40.

Table 3

Raw Data for Test 9 in Field Phase

Time (min)	Psy 1 (μV)	Psy 2 (μV)	Psy 3 (μV)	Psy Avg (μV)	ΔW_1 (grains) [grams]	ΔW_2 (grains) [grams]	ΔW_3 (grains) [grams]	Q_1 (cu ft/min) [m^3/min]	Q_2 (cu ft/min) [m^3/min]	Q_3 (cu ft/min) [m^3/min]	N (passes)	U (ft/sec) [m/sec]	ϕ (degrees)	$\sigma\phi$ (degrees)
0	8.5	4.7	14.3											
15	8.1	6.3	14.2											
30	8.6	3.2	14.4											
45	9.2	2.2	15.5											
60	8.5	3.8	14.1	9.0	1.9907 [0.1290]	1.6126 [0.1045]	1.9244 [0.1247]	41 [1.16]	42 [1.19]	41 [1.16]	85	19.0 [5.79]	77	5.0

Table 4

Pasquil's Atmospheric Stability Categories

σ_θ	Pasquil Stability Category	Stability Class
25.0°	Extremely unstable	A
20.0°	Moderately unstable	B
15.0°	Slightly unstable	C
10.0°	Neutral	D
5.0°	Slightly stable	E
2.5°	Moderately stable	F

The wind direction (ϕ) could be used directly in this equation without adjusting for road bearing because the zero degree heading of the anemometer was aligned parallel to the road being used rather than with true north. The value used for the plume centerline height (H) was zero for all cases, since ground-level emissions were involved; the *Workbook of Atmospheric Dispersion Estimates*[9] recommends this value. Visual observations of the plume indicated that the centerline height was approximately 3 ft (1 m) above ground level. The sampling height of the hi-vols used to measure dust concentrations was also approximately 3 ft (1 m) above ground level; therefore, H actually was zero for all practical purposes.

Knowing the dust emission rate for the road, the emissions per tire were determined by using the traffic frequency in vehicles per second and the number of tires per vehicle.

Using the conversion factor given in the soil psychrometer instruction manual,[10] the soil water potential measurements were converted from microvolts to atmospheres of tension (0.47μV/atmosphere).

Table 5 is the result of performing the above manipulations on the raw data found in Table 3.

It was not possible to plot dust emissions versus soil water potential as was done for the track data, since water potential was

[9] *Workbook of Atmospheric Dispersion Estimates*, p 6.
[10] *Instructions for the MJ55 Psychrometer Microvoltmeter* (unpublished manual) (Wescor, Inc.).

Table 5

Reduced Data for Test 9 in Field Phase

Time (hr)	Psy Avg. (atm of ten.)	X@50' (grains/cu ft) [grams/m3]	X@100' (grains/cu ft) [grams/m3]	U (ft/sec) [m/sec]	ϕ (deg)	σ_z@50' (ft) [m]	σ_z@50' (ft) [m]	N (passes)	Dust Output (grains/tire-mi) [grams/tire-km]
1.0	19.1	8.02×10^{-4}	6.33×10^{-4}	19.0	77	2.3	4.3	85	1.85×10^{3}
		[1.84×10^{-3}]	[1.45×10^{-3}]	[5.79]		[0.7]	[1.3]		[7.45×10^{1}]

not varied during each test but was averaged over the hour. The data were useful, however, for comparing with the track data and for testing the model generated in the first phase.

The linear regression analysis performed on the track data was repeated, using the field data to find whether they fit the same general relationship. The results of the two studies would not be identical even if the test track proved to be a perfect model, since the soil types were not the same; however, it was hoped that they would differ only by a constant. The equation generated with the field data was:

$$\ln D = 5.28 + 0.01T + 0.06S + 0.50W \qquad \text{[Eq 5]}$$

The correlation coefficient for this result was $r = 0.81$, and the standard error was 0.45 over a range of 6.40 to 7.86.

Comparative Data

Data from the third phase of the study were reduced exactly as those from the first phase, since they were of the same form. As mentioned earlier, the only difference in the two phases was the type of soil used in the track.

Table 6 is the reduced data for a test conducted with a vehicle speed of 7.5 mph (12 kph) and a vehicle loading of 2450 lb/tire (1110 kg/tire).

Table 6

Reduced Data for Test 2 in Third Phase

Time (hr)	Psy 1 (atm ten.)	Psy 2 (atm ten.)	Psy 3 (atm ten.)	Psy 4 (atm ten.)	Psy Avg. (atm ten.)	Dust Output (grains/tire-mi)	Dust Output (gm/tire-km)
0.00	10.0	20.9	3.2	22.1	14.0		
0.00	4.3	18.9	3.4	18.3	11.2	1.68×10^{1}	6.76×10^{-1}
1.00	7.9	19.1	4.3	20.2	12.9	2.29×10^{1}	9.22×10^{-1}
1.50	10.9	20.2	3.2	21.5	13.9	5.30×10^{1}	2.13×10^{0}
1.95	13.6	23.4	5.7	26.2	17.2	5.28×10^{1}	2.13×10^{0}
2.40	17.7	28.3	6.8	26.6	19.9	8.00×10^{1}	3.22×10^{0}
2.90	19.6	29.8	5.3	25.5	20.1	8.53×10^{1}	3.43×10^{0}
3.20	26.2	32.1	8.1	29.1	23.9	9.78×10^{1}	3.94×10^{0}

Data Comparison

When this report was written, only three tests had been completed in the third phase of the study. Therefore, an analysis of the form used for the phase one data was not feasible. Instead, these data were inserted into the model generated in the first phase (Eq 3), modified by the addition of a parameter to account for soil type. It was assumed that any differences between results from the two phases could only be attributed to differences in the soils, since all other conditions were identical.

The characteristic used to describe the soil in the equation was plastic limit. This value is a measure of the percent moisture, by weight, contained in a soil when it passes from a plastic to a brittle state while drying. It is near this point that dusting would begin since moisture would be insufficient to bind the soil. Therefore, it is logical that a soil with a higher plastic limit would produce greater emissions at any given moisture level than a soil with a lower plastic limit, since the first soil would be more brittle at that point.

This was true of the two soils used in this study. The soil from the field having a plastic limit of 22 percent produced consistently greater emissions in the test track than did the Gooselake clay which had a plastic limit of 16 percent.

The relationship developed with data from both the first and third phases was:

$$\ln D = -13.05 + 0.12\,T + 0.21\,S + 0.90\,W + 0.48\,P \quad \text{[Eq 6]}$$

where P is the plastic limit of the soil in use and D, S, W, and T are as previously defined in the linear regression analysis.

To determine how well the test track modeled actual conditions, the results of the second and third phases were compared. Since the soils were identical and all parameters were varied over the same ranges in both studies, any differences between the two results could only be attributed to inaccuracies in the test track model.

Dust emissions in the field were consistently higher than they were in the test track for any given set of conditions. The reasons for this were not obvious but were probably related to differences in the aerodynamic properties of the truck and the loading frame. Apparently, more of the dust emitted by the tires was mixed into the airstream by the truck. Since the loading frame did not create as much turbulence in the surrounding air, more dust must have settled onto the track.

The relationship developed with data from all three phases was:

$$\ln D = -5.28 + 0.01\,T + 0.06S + 0.50\,W + 0.48\,P \qquad [\text{Eq } 7]$$

4 FINDINGS

The results of this study indicate that the amount of dust emitted by traffic on unimproved roads is affected by four major factors: vehicle speed, vehicle weight, the road's soil type, and the surface soil water potential. Also, the first phase of the study indicates that a road's age has little bearing on its dusting characteristics.

During this study, certain subjective observations were made about dusting which could not be quantified, but which could be informative nonetheless.

When traffic dries a plastic packed soil, its behavior follows a general pattern. Assuming that the soil originally contains sufficient water, it will be plastic and will deform readily under the pressure of tires passing over it. As the soil dries, it becomes solid, and tread marks are no longer visible; however, the surface remains glossy. Next, the surface dulls as a light coating of dust forms. At this point, dust emissions are very low but it would appear that soon the layer of dust would increase and dusting would become excessive. If the watering rate were determined by the appearance of the road alone, an operator could then decide to spray the road; however, watering at this time would be premature since the soil immediately beneath the dust layer is still quite moist. This moisture apparently is worked to the surface by the sponging action of the soil as it is repeatedly loaded, since the dust layer is controlled and is sometimes reabsorbed onto the road, making the surface glossy again. As the soil continues to dry, the dust layer reappears and increases in depth at a rate proportional to the rate of drying. At high vehicle speeds or low relative humidity, the dust layer will build rapidly; under low vehicle speeds or high relative humidity, the layer can take several hours to develop. When this layer becomes substantial, dusting will be noticeable. It is apparently at this point that the lower layer of soil can no longer supply sufficient moisture to control dusting, and another application of water will be required if emissions are to be maintained within standards. If the road dries further, the surface will begin to develop small cracks, and the soil will become brittle as dusting becomes excessive.

This drying activity is limited to a very thin layer of soil (approximately 1/4 in. [0.6 cm]). The moisture gradient in a road subjected to drying can be very steep, with the soil remaining wet and plastic at a depth of less than 2 in. (5 cm) after the surface has already become dried and brittle. For this reason, the soil psychrometers should be as close to the surface as possible without being exposed to insure that they are describing conditions similar to those at the surface. In the field study, the psychrometers were buried horizontally at a depth of 0.5 in. (1.3 cm); a more shallow depth was attempted but repeated passings of the truck uncovered them.

When the psychrometers became exposed, it was feared that the truck had damaged them, requiring their replacement; however, no damage was done and, once reburied, the units operated as before. Because of the sturdiness of these devices, they seemed particularly well adapted for field use by nontechnical personnel.

At a depth of 0.5 in. (1.3 cm), the psychrometers worked well, but there was an inherent lag between surface conditions and conditions indicated by the psychrometer readings. When a packed road was wetted, approximately 1 hour passed before the psychrometers indicated the change. Also, when two tests were made in the track under identical conditions of vehicle speed and weight, the wetter of the two dusted at a lower average psychrometer reading. The curves of dust output versus soil water potential (see Figure 6) for the two cases were transposed; furthermore, the spread between the curves increased with increasing vehicle speed, i.e., increasing drying rates. These observations all indicate that the lag is due to the soil moisture gradient. This lag apparently had a consistent effect on the final result, since the data for all 18 tests in the first phase had a correlation coefficient of $r = 0.80$ with the equation generated (Eq 3). Also, in a practical situation, if the psychrometers are buried at a depth of 0.5 in. (1.3 cm) the relationship developed in the field study should apply since it was generated under this condition.

Another observation made during this study was the high degree of variation in conditions along the length of a road. Low spots would remain wet and plastic after high spots had begun to dust. There were less dramatic differences between spots of similar appearance, as seen by the variations in psychrometer readings at any given time (Appendix C). These differences were probably due to actual road conditions rather than psychrometer inaccuracies, because the psychrometers were factory-calibrated to within 5 percent of a set value[11] and should therefore differ from each other by no more than 10 percent. Also, it can be seen from the data that no psychrometer read consistently higher or lower than the others throughout the tests, further indicating variable conditions. Because of this inherent variation in moisture conditions, the readings of at least three different psychrometers should be averaged to obtain an accurate indication of overall conditions. Many inexpensive psychrometers can be connected to a common readout unit by using a simple switching mechanism; therefore, the cost of the system does not increase proportionally with its degree of accuracy.

[11] *Instructions for the M155 Psychrometer Microvoltmeter* (unpublished manual) (Wescor, Inc.).

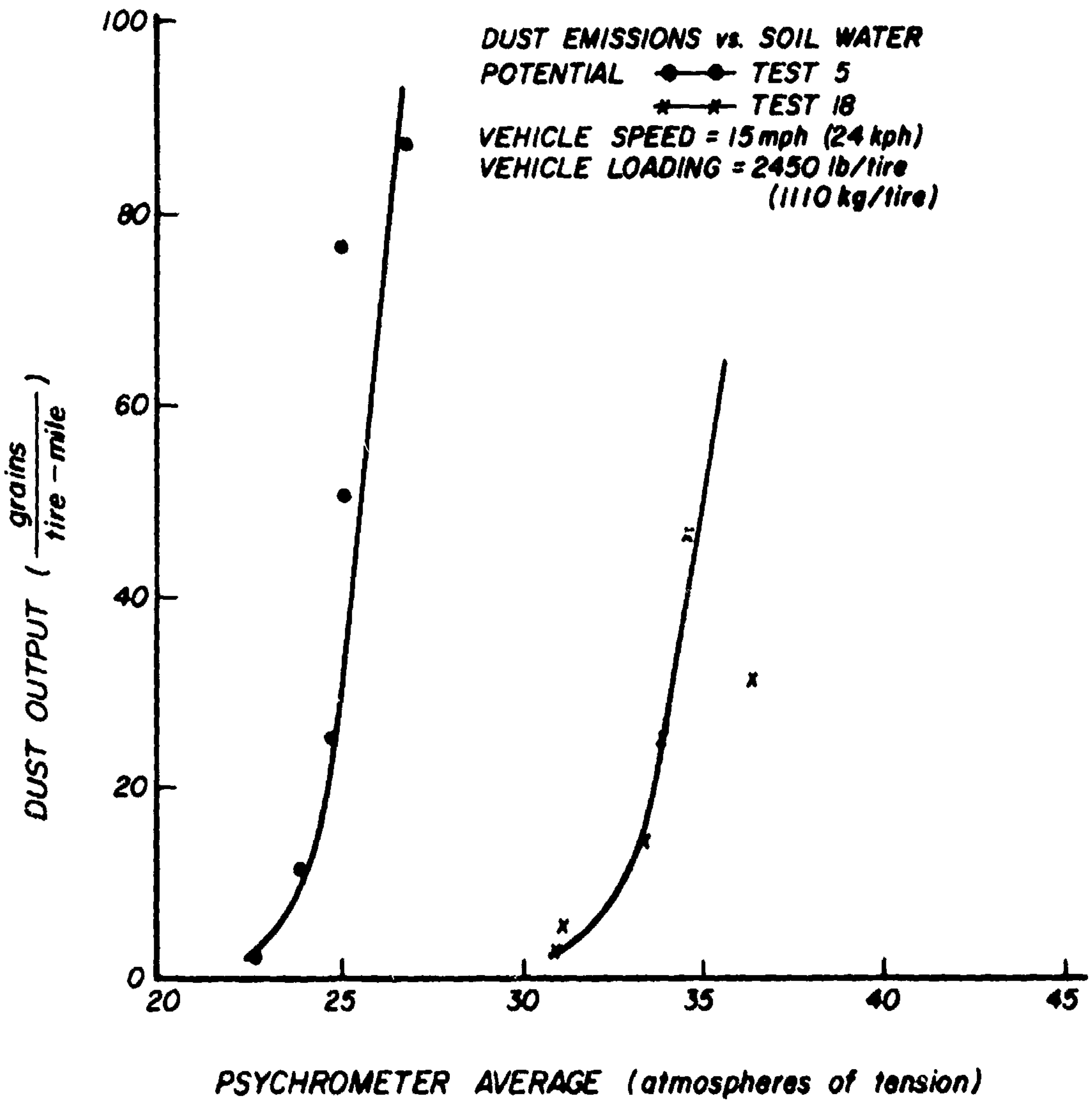

Figure 6. Dust output vs. soil water potential for tests 5 and 18--first phase.

5 CONCLUSIONS

The results of this study indicate that soil water potential is statistically significant in the determination of dust emissions from construction haul roads. Also significant are the speed and weight of the vehicles using the road and the road's soil type. The number of soils studied was insufficient to conclusively state which soil property most accurately determines its dusting characteristics; however, for the two soil types tested, plastic limit was the best indicator.

The most important factor which prevented previous studies from finding a correlation between soil moisture and dusting was probably the method by which the moisture was measured. Obtaining soil samples and measuring their moisture contents in a laboratory allowed greater possibility of error than in an in-situ type of measurement. Also, since water content was measured rather than water potential, dusting conditions were only partially indicated, because factors such as soil compaction and particle size were ignored.

The moisture threshold for dusting originally theorized was not observed in this study. Rather, a single, continuous relationship was found between water potential and dust emissions for all conditions of water potential tested.

The test track used in this study proved to be a useful tool. The features of parameter control, independence from variable weather conditions, and elimination of atmospheric dispersion decreased the amount of data necessary for reliable results. The model generated using the data from the two track phases was:

$$\ln D = -13.05 + 0.12\,T + 0.21\,S + 0.90\,W + 0.48\,P \qquad \text{[Eq 6]}$$

where:

D = Dust emission rate in grains per tire-mile

T = Surface soil water potential in atmospheres of tension

S = Vehicle speed in miles per hour

W = Vehicle weight in thousands of pounds per tire

P = Surface soil plastic limit.

Data taken in the field phase of this study failed to verify the above model exactly; however, the data did fit the same general form of equation. Each parameter had the same effect on dust emissions in both the track and the field, although to a differing degree. This indicates that the test track is a usable simulation of realistic conditions although it is not an exact one. Using the field data and adding the effect of soil type determined in the test track, the following model was developed:

$$\ln D = -5.28 + 0.01\,T + 0.06\,S + 0.50\,W + 0.48\,P \qquad \text{[Eq 7]}$$

When the surface soil water potential, average vehicle speed and weight, and soil plastic limit are all known, the above relationship should be useful in the prediction and control of dust emissions from construction haul roads. Since only one soil type was used in the field, however, the reliability of this equation is certain only for that soil; modification might be necessary to use it for other soils.

6 RECOMMENDATIONS

The findings of this study indicate that further work is warranted in the area of using water as a dust palliative. A more detailed study of the influence soil type has on dust emissions is needed to develop a better defined, less generalized model.

A test track would lend itself well to such a study since many soils could be tested under identical conditions, thereby identifying the property (or properties) of soils which determines their dusting characteristics. Once these properties are identified, further field work would be necessary to validate the findings under realistic conditions.

In any future work, soil water potential should be monitored rather than soil moisture content because of its in-situ measurement capacity and because it appears to consistently indicate when a soil will dust.

APPENDIX A: PROBE ANALYSIS

In the test track, dust emissions were measured using two high-volume air sampler heads mounted in a sampling chamber within a 10-in. (25-cm) duct. All air passing over the track was moved through this duct on its way to a cyclone collector. The hi-vols pulled a portion of this air from the duct and collected the particulates within it. Ideally, there would be complete mixing within the duct, and the concentration of dust within it would simply be the concentration as indicated by the hi-vols. Due to the tendency of particulates to concentrate toward the outside walls of a duct, however, this could not be assumed, and a mass flow analysis was necessary to measure actual mass as a function of indicated mass.

The velocity profile within the duct was first determined to permit isokenetic sampling by using a pitot tube velocity meter. Three concentric regions of equal area were used, with four sampling points in each of the outer two regions and one in the center. The sampling train consisted of a probe, filter holder, venturi flow rate meter, metering valve, vacuum pump, and wet test meter (Figure A1). During the test, dust was generated by the loading frame, and the cyclone and both hi-vols were operating. The probe was held at

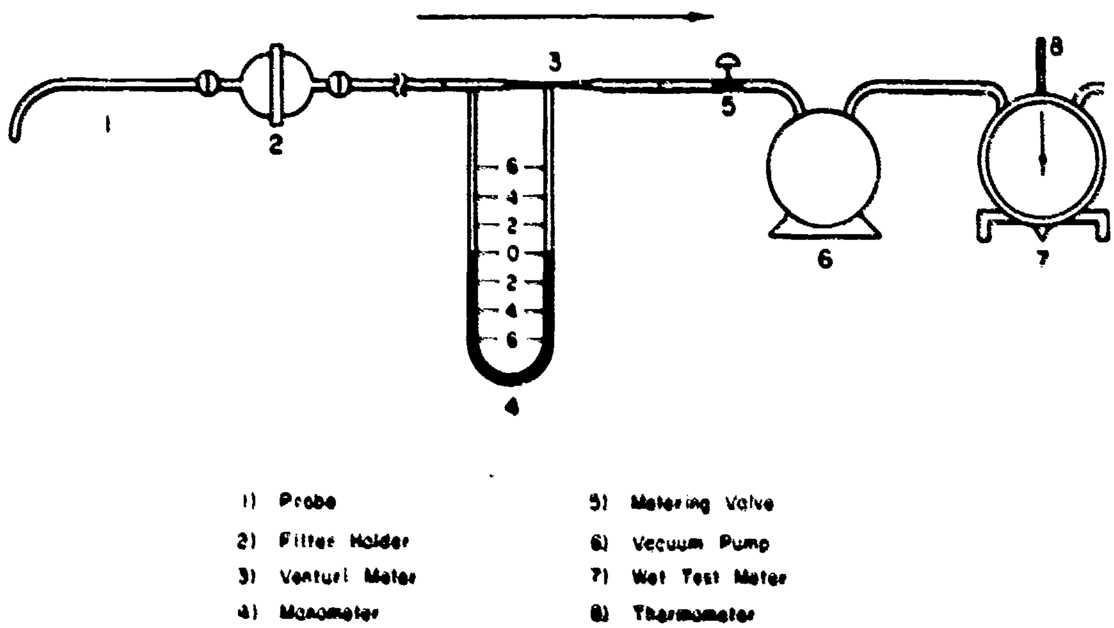

Figure A1. Sampling train.

each outside sampling point for 2 min and at the center point for 8 min to allow for the fact that there was only one point within the center area. At all times the flow through the train was adjusted to match the probe velocity to the duct velocity at that point. The actual concentration of dust within the duct was determined using the mass collected by the probe and the total flow through the probe. This concentration was then compared to the hi-vol concentration.

Hi-vol 1 flow rate	40.5 cu ft/min (1.15 m^3/min)
Hi-vol 2 flow rate	39.5 cu ft/min (1.12 m^3/min)
Probe total flow	20.8 cu ft (0.59 m^3)
Hi-vol 1 mass collected	2.960 grains (0.1918 gm)
Hi-vol 2 mass collected	2.681 grains (0.1737 gm)
Probe mass collected	0.0679 grain (0.0044 gm)
Sampling time	24 min

Hi-vol flow = (40.5 cu ft/min + 39.5 cu ft/min) x 24 min = 1920 cu ft

$$((1.15\ m^3/\text{min} + 1.12\ m^3/\text{min}) \times 24\ \text{min} = 54.48\ m^3)$$

Probe flow = wet test meter reading = 20.8 cu ft (0.59 m^3)

$$\text{Hi-vol concentration} = \frac{5.641\ \text{grains}}{1920\ \text{cu ft}} = 2.94 \times 10^{-3}\ \text{grains/cu ft}$$

$$\left(\frac{0.3655\ \text{gm}}{54.48\ m^3} = 6.71 \times 10^{-3}\ \text{gm}/m^3\right)$$

$$\text{Duct concentration} = \text{probe concentration} = \frac{0.0679\ \text{grain}}{20.8\ \text{cu ft}} = 3.26 \times 10^{-3}\ \frac{\text{grain}}{\text{cu ft}}$$

$$\left(\frac{0.0044\ \text{gm}}{0.59\ m^3} = 7.46 \times 10^{-3}\ \text{gm}/m^3\right)$$

$$\frac{\text{Actual concentration}}{\text{Indicated concentration}} = \frac{\text{Duct conc.}}{\text{Hi-vol conc.}} = \frac{2.94 \times 10^{-3}\ \text{grain/cu ft}}{3.26 \times 10^{-3}\ \text{grain/cu ft}} = .90$$

$$\left(\frac{6.71 \times 10^{-3}\ \text{gm}/m^3}{7.46 \times 10^{-3}\ \text{gm}/m^3} = .90\right)$$

This indicates that the dust concentration as indicated by the hi-vols was 90 percent of the actual concentration in the duct. All values of dust concentration were therefore divided by 0.90 when calculating the dust emission rate.

APPENDIX B: SOIL WATER POTENTIAL AND SOIL PSYCHROMETERS

Water content only partially indicates the effect water has on soil properties. Another very important consideration is the water's energy state. In fact, some experts think that the most important physical soil characteristic other than water content is the energy state of that water.[12] The energy state of soil water is a relatively new concept to soil physics and is not yet fully understood; however, a large body of mathematical theory has been developed on the subject.

A distinction is made between systems which involve both kinetic and potential energies of water and systems which deal only with potential energy. In this study, only potential energy was considered, since there was no rapid movement of water.

Many forces act on water held in a soil matrix. The potential energy which a given unit of water contains is the force required to move it a unit distance against the sum of these forces. When the unit of water is chosen on a volumetric basis, the potential energy (or potential) has dimensions identical to those for pressure ($F \cdot L/L^3 = F/L^2 = M/(LT^2)$), and is expressed in negative bars to negative atmospheres. The potential is negative because work must be done on the water to move it rather than work being done by it. For convenience, potential is expressed in terms of tension, making all values positive--hence, the units "atmospheres of tension."

Water potential is the sum of five subpotentials--matric, gravity, pressure, osmotic, and overburden--each of which is associated with a different force acting on the water. When a reading is taken with a soil psychrometer, the sum of all five subpotentials is being measured, since the forces creating them are additive by nature.

Water potential is a good parameter for describing soil conditions and studying dust emissions, because many factors contribute to it. Degree of soil compaction, relative humidity, water content, soil particle size, and ions present all influence a soil's water potential.

One method of measuring soil water potential is with a soil tensiometer. This instrument measures the force on a column of water acting through a porous plate buried in the soil. At a tension of 0.85 atmospheres (-0.85 atmosphere of pressure), cavitation begins in the pores of the plate, making this value the upper limit of operation for a tensiometer filled with water. Other tensiometers

[12] L. D. Baver, W. H. Garder, and W. R. Gardner, *Soil Physics* (John Wiley and Sons, Inc., 1972), p 291.

using less volatile fluids can operate at higher tensions, but none are practical for use above 10 atmospheres. Since this study required a range between 15 and 50 atmospheres of tension, a different instrument was needed.

A means of measuring soil water potential in very dry soils is possible with the use of a soil psychrometer. The psychrometer itself is a hollow ceramic bulb 0.25 in. (6 mm) in diameter and 0.75 in. (19 mm) long. Four wires project from one end of the bulb, and a rubber insulator encases half of the bulb and part of the four wires. The whole unit (excluding leads) is 0.32 in. (8 mm) in diameter and 1.85 in. (47 mm) long. Due to its small size, the unit is easily buried and can withstand the force of a truck passing over it. Within the hollow section of the bulb is a thermocouple junction.

During operation, the psychrometer leads are connected to a power supply-readout unit. To take a reading, the unit is switched to the read mode and the meter is adjusted to indicate zero microvolts. This is the reference output of the psychrometer's thermocouple and is a function of the dry-bulb temperature within the soil. The unit is then switched to the cooling mode, in which a current is supplied to the thermocouple which cools it to below the dew point temperature. Moisture within the soil's air spaces is then forced to condense onto the thermocouple junction. After cooling for a few seconds, the unit is switched to the dew point mode, which alternately reads the thermocouple output and supplies a pulse of cooling current inversely proportional to that output. As the junction warms, the moisture on it begins to evaporate, taking heat from the thermocouple. When the dew point temperature is reached, an equilibrium condition is set up, since any further evaporation will lower the junction's temperature below the dew point. This lower temperature causes water to condense onto the junction, which produces heat and warms the thermocouple to the dew point. If the temperature of the thermocouple increases to above the dew point, moisture will evaporate, which removes heat from the junction and returns the temperature to the dew point. The pulses of cooling current are necessary because the system is not ideal, and heat from sources other than the condensation of water vapor is applied to the junction. If the thermocouple were perfectly thermally isolated as the theory assumes, this current would not be necessary, and the dew point temperature would be held indefinitely.

When the unit is in the dew point mode, the meter indicates the voltage produced by the thermocouple. Initially the needle will either rise or fall but will eventually level off at a given value. At this point, the thermocouple is at the dew point temperature, and the reading indicated by the meter is proportional to this temperature. Since the meter had already been adjusted to read zero at the dry-bulb temperature, the difference between wet-bulb and dry-bulb temperatures is indicated, which is a measure of the relative humidity within the soil's air spaces. This is a direct indication of the soil water potential, since the amount of water in the air between the soil particles is a function of the amount of water present on the particles and the force with which that water is bound. If the water is held tightly to the particles, little will escape into the vapor phase; however, if it is held loosely, much will evaporate, making the relative humidity high and the difference between wet-bulb and dry-bulb temperatures low.

APPENDIX C: COMPLETE LISTING OF REDUCED DATA

FIRST PHASE

TEST TRACK LOADED WITH GOOSELAKE CLAY

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (LOAD LBS/TIRE)	TIME (HR)	PSV 1 (ATM TEN)	PSV 2 (ATM TEN)	PSV 3 (ATM TEN)	PSV 4 (ATM TEN)	PSV AVERAGE (ATM TEN)	HI-VOL DELTA W (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/TIRE-MILE)
1	6.8	2.65	0.90	30.9	23.4	45.3	40.6	35.1			
			2.00	31.3	24.5	44.9	41.5	36.6	0.5346	75.5	1.42
			4.00	34.3	23.0	51.3	46.0	38.7	1.8102	74.5	4.85
			5.90	47.2	36.5	65.5	63.8	52.3	5.3333	74.0	15.1
			6.90	52.3	36.6	67.9	59.1	54.0	4.0849	76.0	23.8
2	15.9	1.85	0.80	29.6	31.1	50.2	37.2	37.0			
			0.50	32.3	32.6	51.9	40.0	39.1			
			1.00	32.1	32.1	50.4	37.7	38.1	17.941	73.0	32.7
			1.90	33.0	31.1	51.3	39.1	38.7	46.555	79.5	86.5
			2.40	34.0	39.4	52.6	39.6	39.1	43.347	79.0	148
			2.90	34.3	30.0	52.6	41.7	39.6	60.734	77.5	208
3	7.5	2.65	0.00	36.2	26.8	45.5	28.9	34.5			
			1.00	35.3	28.1	46.6	31.1	36.0			
			2.20	37.4	27.2	47.7	31.7	34.0	5.2314	73.5	8.60
			3.00	39.8	25.7	48.7	32.8	36.8			
			4.10	63.8	27.4	52.1	34.3	39.4	25.704	72.5	49.6
			5.10	60.1	38.6	60.0	34.3	44.3	32.244	71.0	121
			5.45	53.4	33.4	63.6	35.1	46.4	28.322	72.0	139
4	6.5	2.25	0.00	19.6	40.9	40.2	35.7	34.0			
			1.00	16.6	41.7	37.9	39.6	33.8	0.9707	75.0	3.44
			2.10	23.2	38.1	41.3	38.7	35.3	3.7700	74.5	12.2
			3.00	32.1	35.7	41.3	40.2	37.4	11.035	74.0	44.1
			3.85	37.2	35.5	47.0	43.4	40.9	15.605	7395	79.4
			4.85	43.4	37.4	49.4	39.6	42.6	24.268	70.5	87.2
5	15.9	2.65	0.90	25.5	23.2	18.1	17.0	21.1			
			0.50	24.7	24.0	20.6	20.4	22.6	0.6713	76.0	2.35
			1.05	25.1	23.8	22.8	23.6	23.8	3.6774	75.5	11.8
			1.50	24.5	24.5	26.0	23.6	24.7	6.4382	75.0	25.4
			2.00	25.7	22.6	25.5	26.4	25.1	14.043	74.0	59.5
			2.45	26.6	18.3	27.4	27.9	25.1	18.447	73.8	76.3
			3.00	28.5	20.0	28.5	29.9	26.8	26.157	72.8	87.9
			3.25	30.0	23.0	29.1	32.3	28.7	19.065	74.0	137

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (1000 LBS/TIRE)	TIME (HR)	PSY 1 (ATM TEN)	PSY 2 (ATM TEN)	PSY 3 (ATM TEN)	PSY 4 (ATM TEN)	PSY AVERAGE (ATM TEN)	HI-VOL DELTA W (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/TIRE-MILE)
6	7.5	2.65	0.00	33.0	11.9	21.1	13.8	20.0			
			0.50	36.4	15.1	27.2	20.4	24.9			
			1.00	36.0	14.0	30.0	22.3	25.5	1.2639	74.5	4.51
			1.50	39.6	15.3	35.3	26.2	29.1			
			2.00	37.2	15.4	36.4	25.7	28.9	1.0796	74.0	6.75
			2.50	37.9	16.0	37.4	30.0	30.4			
			2.95	39.6	16.4	37.2	32.1	31.3	4.6157	75.0	17.2
			3.40	42.1	18.1	40.0	34.9	33.8			
			3.75	42.6	14.9	41.7	37.2	34.0	7.4907	73.5	33.9
			4.50	46.2	20.4	45.3	41.9	38.5			
			4.75	47.7	22.3	44.7	39.4	38.5	14.954	73.0	54.5
			5.15	48.1	25.7	47.2	43.8	41.3	9.6163	74.0	88.2
7	7.	1.85	0.00	45.5	14.9	13.2	22.3	24.0			
			0.50	46.2	19.1	20.2	26.0	21.9			
			1.00	41.5	15.7	19.1	23.6	25.1	0.6157	73.5	2.23
			1.50	31.9	14.7	17.2	22.1	21.5			
			2.00	32.3	15.1	20.2	25.3	23.2	MAL	MAL	MAL
			2.50	25.5	20.4	2.94	35.1	27.7			
			3.05	36.2	19.6	30.4	34.5	30.2	1.6759	74.5	5.70
			3.50	36.2	20.9	33.6	39.1	32.6			
			4.00	36.2	20.9	34.7	39.4	32.8	4.4182	76.0	16.3
			4.50	37.2	21.3	38.1	44.0	35.1			
			5.00	39.4	23.8	39.4	45.7	37.0	8.6234	75.5	34.4
			5.40	43.4	23.8	40.9	46.6	38.7	5.1543	78.5	43.7
8	5.0	1.85	0.00	19.1	21.3	18.3	30.9	22.3			
			0.50	19.4	19.4	17.6	32.8	22.3			
			0.95	18.7	19.6	21.9	33.4	23.4	0.2901	77.5	1.57
			1.40	19.1	19.4	24.3	35.5	23.4			
			1.80	18.1	18.1	25.1	35.1	24.0	0.1096	77.5	0.66
			2.40	16.6	18.3	26.2	38.3	24.9			
			2.70	15.3	15.5	24.5	37.9	23.4	0.1003	77.0	0.59
			3.10	15.3	16.0	22.6	34.5	22.1			
			3.60	15.7	14.5	22.8	34.7	21.9	0.1111	76.5	0.64
			4.20	16.2	13.8	25.1	33.4	22.1			
			4.65	18.7	13.6	25.7	35.1	23.4	0.2407	76.0	1.20
			5.20	20.2	14.3	28.3	37.4	25.1			
			5.35	23.2	16.6	30.9	39.1	27.4	0.3395	76.5	1.97
			NEXT	DAY							
			5.55	36.9	22.6	44.7	48.1	38.5			
			6.00	38.7	22.1	45.7	50.4	39.4			
			6.55	38.7	22.3	45.5	50.0	39.1	0.3117	76.5	1.63
			7.00	39.4	22.3	46.2	53.2	40.2			
			7.55	39.8	20.2	47.9	54.3	40.6	0.8287	76.5	4.32
			8.00	43.8	27.2	49.1	54.5	43.6			
			8.45	44.3	26.0	49.6	56.4	44.0	0.9861	76.0	5.75
			9.00	43.6	24.5	50.4	55.5	43.6			
			9.50	44.5	23.8	52.6	59.4	45.1	1.9089	75.5	9.61
			10.00	48.1	26.8	55.5	63.6	48.5	1.0602	77.0	11.0

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (1000 LBS/ TIRE)	TIME (HR)	PSY 1 (ATM TEN)	PSY 2 (ATM TEN)	PSY 3 (ATM TEN)	PSY 4 (ATM TEN)	PSY AVERAGE (ATM TEN)	HI-VOL DELTA W (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/ TIRE-MILE)
9	15.0	2.25	0.00	27.9	8.7	18.1	35.7	22.6			
			0.35	33.2	9.6	24.5	39.6	26.8	0.5093	77.0	2.51
			0.85	33.6	8.7	28.5	39.6	27.7	5.1512	77.0	17.8
			1.30	36.6	8.9	30.2	41.7	29.4	13.785	76.0	53.6
			1.80	40.6	8.9	33.4	43.6	31.7	29.586	74.0	106
			2.10	40.9	9.4	33.0	41.4	31.7	35.418	72.0	131
10	5.0	2.25	0.00	19.1	MAL	13.0	11.1	14.5			
			0.50	23.6	MAL	16.4	10.6	16.8			
			0.90	23.4	MAL	17.4	16.0	18.9	0.5447	77.0	3.14
			1.50	24.3	MAL	20.0	18.1	20.9			
			1.90	25.3	MAL	22.6	19.4	22.3	0.2207	77.0	1.14
			2.50	27.9	MAL	25.5	20.9	24.7			
			2.80	26.9	MAL	28.7	24.0	27.2	0.3827	77.0	2.20
			3.30	32.6	MAL	30.6	27.2	30.2			
			3.75	34.0	MAL	33.0	31.9	33.0	0.7701	76.5	4.23
			4.35	38.5	MAL	35.7	34.7	36.4			
			4.70	40.0	MAL	36.2	36.2	37.4	3.7095	76.0	20.5
			5.35	42.6	MAL	41.5	40.9	41.7			
			5.70	46.6	MAL	44.5	40.9	44.0	3.3966	77.5	17.5
11	15.0	2.25	0.00	24.7	16.2	15.3	32.8	22.2			
			0.50	25.5	6.4	13.0	30.9	18.9	1.0725	76.0	3.75
			1.00	22.1	5.3	20.4	35.3	20.9	MAL	MAL	MAL
			1.50	25.7	6.2	24.3	38.3	23.6	3.3765	75.5	11.9
			2.00	25.7	9.6	26.8	43.0	26.4	8.2253	75.0	29.2
			2.45	26.4	11.3	29.6	46.2	28.3	13.475	76.0	52.4
			3.00	29.8	13.2	31.9	51.3	31.5	20.000	74.5	64.9
			3.45	31.5	17.2	36.2	54.5	34.9	22.741	76.0	88.4
12	7.5	2.45	0.00	25.3	16.0	6.2	37.9	21.3			
			0.50	27.4	19.1	8.7	40.0	23.8			
			1.05	24.5	18.3	8.1	39.1	22.6	0.8750	76.0	2.92
			1.50	26.0	20.2	11.3	29.8	24.3			
			2.00	26.2	20.2	13.4	38.3	24.5	2.6620	76.0	9.80
			2.50	28.5	21.1	14.3	41.1	26.2			
			2.90	31.7	21.3	15.5	43.0	27.9	7.0169	74.5	27.8
			3.40	34.5	24.0	21.5	48.9	32.3			
			3.85	ND	ND	ND	ND	ND	14.400	76.0	53.0
			4.30	38.5	29.1	25.7	53.6	36.6			
			4.75	42.1	31.1	30.0	59.4	40.6	22.125	76.5	85.5
			5.25	47.0	33.2	31.7	63.0	43.8	13.048	79.5	87.3
			5.75	48.9	35.5	35.3	63.6	45.9	19.952	78.0	136
13	5.0	2.45	0.00	36.6	17.0	13.8	12.1	20.0			
			0.50	38.7	21.3	16.8	16.0	23.2			
			1.05	39.1	20.9	18.3	17.9	24.0	0.5463	80.0	2.59
			1.50	36.8	19.8	20.9	17.9	23.8			
			2.05	38.9	21.1	24.7	20.4	26.3	0.4367	80.0	2.18
			2.50	41.7	22.6	27.4	21.9	28.5			
			3.05	42.1	22.6	29.4	26.0	30.0	1.0833	79.5	5.44
			3.50	44.9	24.9	33.2	30.9	33.4			
			4.00	47.9	30.2	38.5	34.0	37.7	2.4846	78.0	13.4
			4.50	48.9	30.2	39.8	38.5	39.4			
			5.00	MAL	34.3	42.3	41.3	39.4	4.3410	78.0	22.2
			5.50	50.0	35.7	45.7	41.5	43.2	3.0247	79.0	30.5

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (1000 LBS/TIRE)	TIME (HR)	PSY 1 (ATM TEN)	PSY 2 (ATM TEN)	PSY 3 (ATM TEN)	PSY 4 (ATM TEN)	PSY AVERAGE (ATM TEN)	HI-VOL DELTA W. (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/ TIRE-MILE)
14	7.5	2.25	0.00	MAL	38.9	21.1	23.2	27.7			
			0.50	MAL	39.4	23.2	27.9	30.2			
			1.00	MAL	34.5	22.1	24.9	27.2	0.8318	79.5	2.78
			1.50	MAL	31.9	23.6	27.2	27.7			
			2.00	MAL	33.4	26.8	30.0	30.0	2.6836	78.0	9.15
			2.50	MAL	34.9	28.3	32.8	31.9			
			2.95	MAL	37.9	31.1	35.1	34.7	7.8827	78.0	28.3
			3.50	MAL	38.7	33.8	39.1	37.2			
			3.90	MAL	41.3	34.0	39.6	38.3	16.268	75.5	60.3
			4.40	MAL	44.9	37.4	40.4	40.9	13.275	77.0	91.7
			4.90	MAL	47.2	40.2	42.6	43.4	15.241	76.0	107
15	7.5	1.85	0.00	32.1	57.4	22.8	28.9	35.3			
			0.50	34.0	65.5	30.0	35.3	41.3			
			1.05	31.8	61.7	32.1	36.6	41.1	1.9568	80.5	6.16
			1.50	34.5	59.1	33.6	38.3	41.5			
			2.00	40.2	56.1	34.0	39.8	40.0	8.4783	79.5	29.9
			2.50	32.6	57.9	36.2	42.1	42.3			
			3.00	36.2	60.9	37.7	44.5	44.9	16.378	77.5	56.2
			3.45	37.9	63.6	39.4	46.2	46.8	11.497	79.5	85.5
16	5.0	1.85	0.00	ND	ND	ND	ND	ND			
			0.50	25.5	40.4	10.4	15.7	23.2			
			1.00	22.6	37.0	10.6	14.0	21.1	0.3648	80.5	1.83
			1.50	22.3	34.3	11.7	14.0	20.6			
			2.00	23.2	34.3	13.4	14.3	21.3	0.1991	80.0	0.99
			2.50	23.6	33.4	14.9	17.7	22.3			
			2.95	25.3	33.6	16.8	20.2	24.0	0.2562	80.5	1.34
			3.50	25.5	33.8	20.0	24.0	26.0			
			3.90	27.7	34.5	22.3	27.0	27.9	0.5432	80.5	2.83
			4.45	30.0	35.7	23.8	31.1	30.2			
			4.90	32.3	38.3	25.1	35.7	33.0	1.3272	79.5	6.66
			5.45	33.4	39.4	27.2	36.2	34.0			
			5.85	34.9	41.1	29.8	38.1	36.0	2.2700	79.5	12.0
			NEXT	DAY							
			5.85	55.7	69.8	49.4	57.2	58.1			
			6.40	58.5	68.7	45.7	56.4	57.4			
			6.85	55.3	66.0	46.6	56.4	56.2	1.9630	81.0	9.67
17	5.0	2.25	0.00	26.4	37.4	16.6	18.1	24.7			
			0.50	24.3	35.3	18.1	18.3	24.0			
			1.00	22.8	33.2	18.3	20.0	23.6	0.4028	79.0	2.03
			1.50	22.6	30.6	19.4	20.2	23.2			
			2.00	21.1	28.7	21.3	22.6	23.4	0.2269	78.5	1.15
			2.50	22.1	29.4	23.2	23.8	24.7			
			3.10	22.3	27.4	24.3	24.9	24.7	0.2145	79.0	0.99
			3.40	22.6	26.4	24.0	24.3	24.3			
			3.85	22.8	26.2	26.4	26.6	25.5	0.2160	79.5	1.45
			4.30	23.4	27.4	28.1	27.2	26.6			
			4.90	26.4	27.9	29.1	27.7	27.2	0.5000	78.5	2.42
			5.30	24.5	26.4	29.6	30.2	27.7			
			5.85	27.0	28.5	32.3	32.8	30.2	0.5880	78.0	3.17
			6.25	28.9	30.6	35.7	34.5	32.6			
			6.85	29.6	30.6	37.2	36.2	33.4	1.0772	77.5	5.54
			7.25	32.8	33.8	40.0	37.2	36.0			
			7.60	34.9	36.0	45.5	40.6	39.4	1.5555	79.0	8.27

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (1000 LBS/ TIRE)	TIME (HR)	PSY 1 (ATM TEN)	PSY 2 (ATM TEN)	PSY 3 (ATM TEN)	PSY 4 (ATM TEN)	PSY AVERAGE (ATM TEN)	HI-VOL DELTA W (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/ TIRE-MILE)
18	15.0	2.45	0.00	34.0	34.5	21.5	26.6	29.1			
			0.45	36.4	39.5	21.9	25.7	30.9	0.8750	80.5	3.21
			0.95	36.0	37.2	24.9	25.7	31.1	1.4846	80.0	4.93
			1.40	37.4	39.6	28.7	MAL	33.4	3.8287	79.0	14.3
			[illegible]	36.8	38.7	29.1	MAL	33.8	7.2192	78.5	24.5
			2.40	39.4	42.8	32.1	MAL	36.4	9.3194	78.5	31.6
			[illegible]	[illegible]	[illegible]	[illegible]	MAL	[illegible]	[illegible]	78.0	[illegible]
19	15.0	1.45	0.00	25.5	38.3	6.0	MAL	23.2			
			0.50	27.9	38.9	4.9	MAL	23.8			
			1.00	[illegible]	36.2	5.5	MAL	23.4	0.8410	79.5	1.41
			[illegible]	[illegible]	[illegible]	7.0	MAL	[illegible]			
			1.90	25.5	33.2	7.4	MAL	22.1	3.0802	79.5	5.72
			[illegible]	[illegible]	34.9	11.7	MAL	25.1			
			3.00	28.9	34.9	12.6	MAL	25.5	11.495	78.5	17.7

SECOND PHASE

FIELD EXPERIMENT

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (1000 LBS/ TIRE)	TIME (MIN)	PSE AVERAGE (ATM TEN)	AM(50') (GRAINS/ CU FT)	AM(100') (GRAINS/ CU FT)	PHI (DEG)	SIGMA-Z @50' (FT)	SIGMA-Z @100' (FT)	U (FT/SEC)	N (#PASSES)	DUST OUTPUT (GRAINS/ TIME-MILE)
1	10	[illegible]	[illegible]	11.9	.262E-01	[illegible]	105	4.6	8.5	10.4	125	[illegible]
2	7	1.37	1.0	65.1	.571E-03	.342E-03	70	4.6	8.5	9.5	89	1060
3	15	1.37	1.0	95.5	.236E-02	.124E-02	104	3.9	6.9	11.0	148	2600
4	10	[illegible]	[illegible]	[illegible]	.151E-02	.916E-03	101	6.2	13.1	7.4	121	2470
5	15	[illegible]	1.0	[illegible]	.552E-02	.207E-02	100	6.2	13.1	6.5	154	5430
6	10	1.93	1.0	24.7	.142E-02	.941E-03	90	4.6	8.5	11.0	121	2530
7	7	1.93	1.0	31.3	.509E-03	.278E-03	80	2.6	4.9	13.0	96	723
8	10	1.93	1.0	113.2	.105E-02	.602E-03	102	3.9	6.9	13.8	121	1720
9	7	2.50	1.0	19.1	.802E-03	.633E-03	77	2.3	4.3	19.0	85	1850
10	15	2.50	0.8	22.1	.146E-02	.833E-03	70	2.3	4.3	14.0	118	[illegible]
11	10	2.50	1.0	81.3	.106E-02	.480E-03	100	2.9	5.6	17.0	108	2270

THIRD PHASE

TEST TRACK LOADED WITH FIELD SOIL

TEST NO.	VEHICLE SPEED (MPH)	VEHICLE LOADING (STAND LOAD TIMES)	TIME (MIN)	PSV 1 (ATM TEN)	PSV 2 (ATM TEN)	PSV 3 (ATM TEN)	PSV 4 (ATM TEN)	PSV AVERAGE (ATM TEN)	HI-VOL DELTA W (GRAINS)	HI-VOL FLOW (CFM)	DUST OUTPUT (GRAINS/ TIRE-MILE)
1	5.0	2.65	0.00	10.6	9.6	3.2	11.1	8.6			
			1.00	13.6	5.5	4.0	11.7	8.7	0.9537	81.0	4.70
			2.00	20.6	13.7	3.2	11.7	11.8	1.7731	80.0	8.86
			3.00	26.4	15.1	4.0	14.7	15.2	2.8906	78.5	14.7
			3.95	29.1	17.7	7.2	15.5	17.4	3.9815	78.5	21.3
			4.90	37.0	18.9	8.3	17.4	20.4	5.1265	78.5	27.4
			5.85	39.1	23.4	10.4	17.0	22.5	6.4382	78.0	34.7
2	7.5	2.65	0.00	10.0	20.9	3.2	22.1	14.0			
			0.50	4.3	18.9	3.4	18.3	11.2	2.4737	78.5	14.8
			1.00	7.9	19.1	4.3	20.2	12.9	3.3540	78.0	22.9
			1.50	10.9	20.2	3.2	21.5	13.9	7.7762	78.0	53.0
			1.95	11.6	23.4	5.7	26.2	17.2	6.0750	77.3	52.8
			2.40	17.7	24.3	6.8	26.6	19.9	10.356	76.5	80.0
			2.91	19.6	29.6	5.3	25.5	20.1	12.165	76.0	85.3
			3.20	25.2	32.1	8.1	29.1	23.9	8.4922	77.0	97.8
3	15.0	2.65	0.00	10.6	15.1	17.0	5.3	12.0			
			0.50	12.1	12.8	9.6	11.7	11.6	3.5123	80.5	11.6
			1.00	11.9	16.0	14.3	11.7	13.5	9.1482	79.0	39.9
			1.50	12.8	17.0	18.5	14.9	15.8	12.946	78.0	44.1
			1.75	15.1	19.1	20.9	14.8	18.0	14.150	79.0	95.3

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